MEG analysis of ~~photonuclear events and~~ pileup handling

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PIONEER collaboration meeting
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MEG (II) LXe detector:
reconstruction

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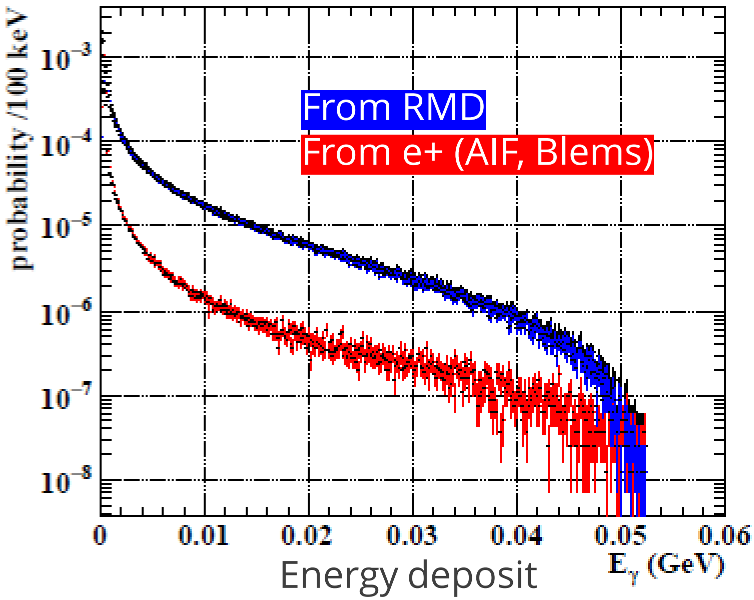
PIENUX seminar, 2nd Nov. 2021

東京大学 THE UNIVERSITY OF TOKYO

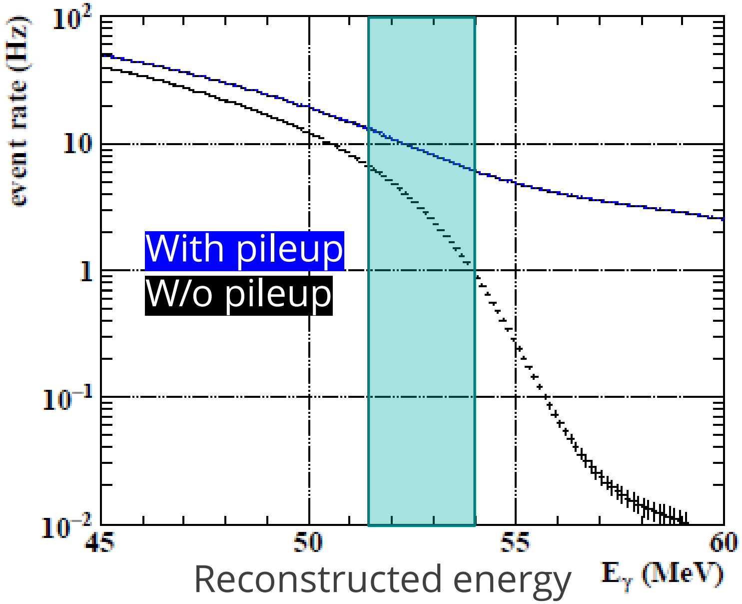
ICEPP The University of Tokyo

研究拠点形成事業 Core-to-Core Program



Photon hit rate: 0.5 MHz

- E_{dep}> 0.2 MeV, $R_\mu = 5\times10^7\ s^{-1}$
- in the active LXe (no segmentation)
- Rate increases with smaller E_γ (infrared divergent)



BG in signal region increases by ×2.8

- [51.5, 54] MeV
- 64% of triggered events contain pileup
- Hence, we don't want to simply throw away pileup events.

Challenges and issues

1. Sensor and light-yield stability
   calibrate, calibrate, and calibrate

2. Shower fluctuation
   Largest source of limitation in reconstruction

3. Lack of MC reproducibility
   Expected energy resolution turned out to be not achieved

4. Interaction before active volume
   Leakage of shower and light from inner face
   Limit the detection efficiency and causes lower-energy tail

All these affects pileup analysis

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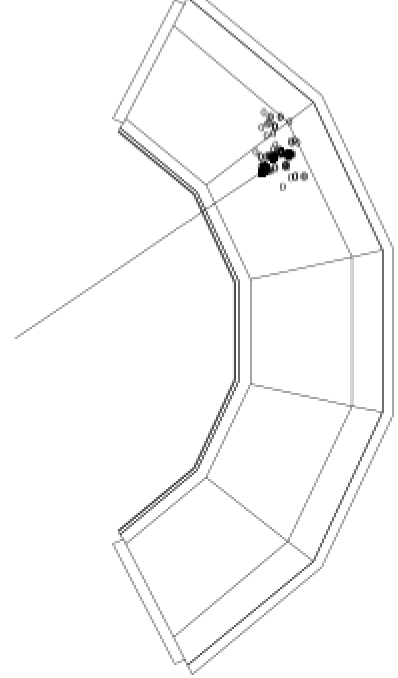
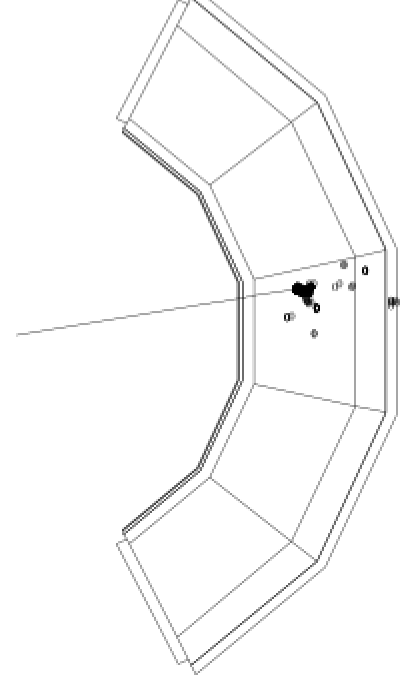
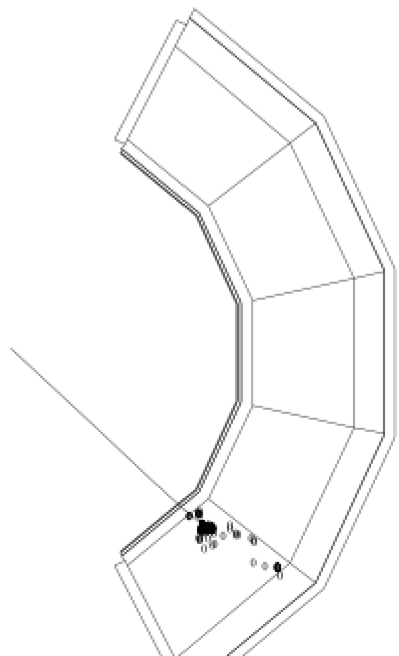


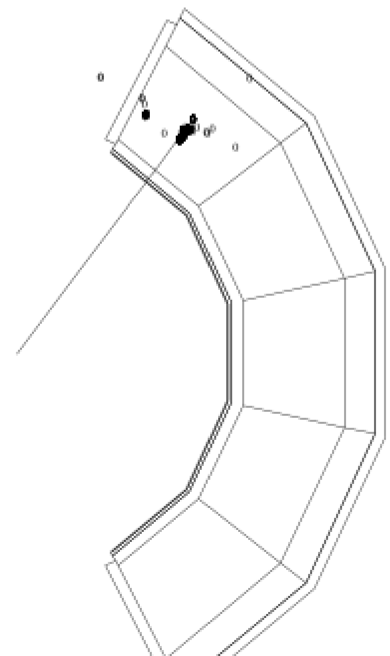
EVENT 3



EVENT 4

Large event-by-event fluctuation





Today’s topics

Minimal review of algorithms in MEG/MEG II

Limiting factors

Suggestion for possible way to improve

Advice to be and not to be attempted

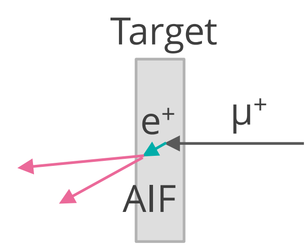
To stimulate further discussion and studies.

What are “pileup” in MEG?

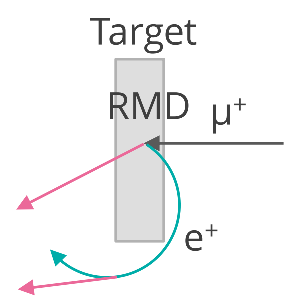
1. Accidental superposition of multiple photons (off-timing pileup)

- No correlation in time, position, or energy
- Usually, separated in time → can be identified by time distribution or waveform
  can be unfolded in waveform
- but can be “on-time” at some probability.
- Fraction ∝ beam rate

2. Correlated multiple photon events (on-timing pileup)



- Due to physical processes, such as AIF 2γ, RMD + Brems
- Time coincident, some position and/or energy correlations
- Cannot be identified by time or waveform
  Can be identified with light distribution. Difficult to unfold.
- Fraction = const.



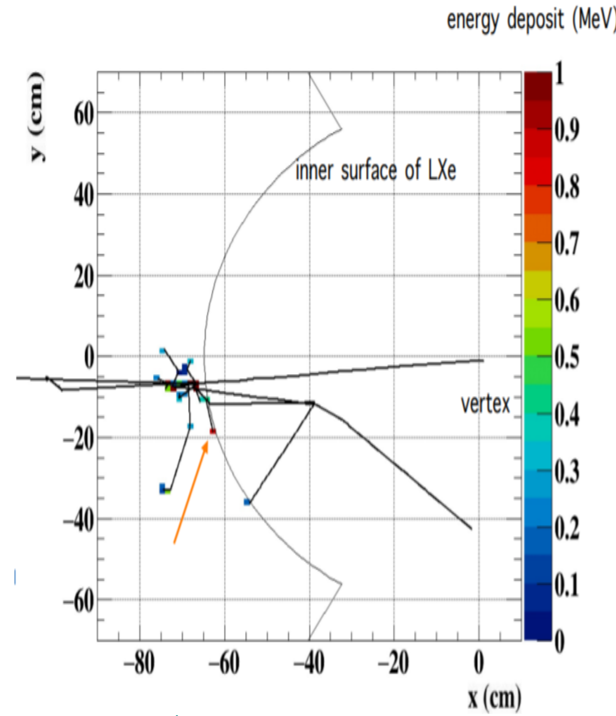
- These are BG, so don’t have to recover them.

What are NOT pileup?

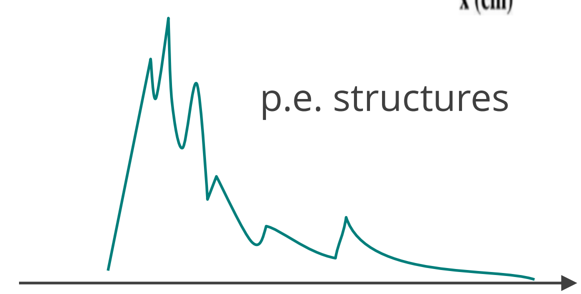
1. Conversion before LXe
2. Isolated shower components
3. Scint. photon statistical fluctuation

We should sum up these components to reconstruct energy.
Eliminating them results in low-energy tail.

PIONEER case: Brems. from positron?



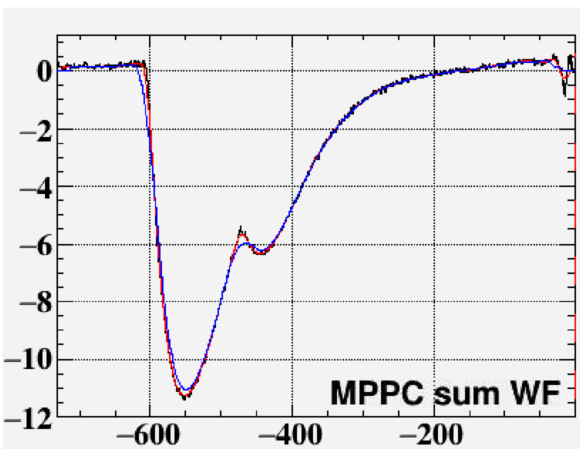
4. Too small photon ($\ll$ energy reso.)
   - Photon generation is infrared divergent

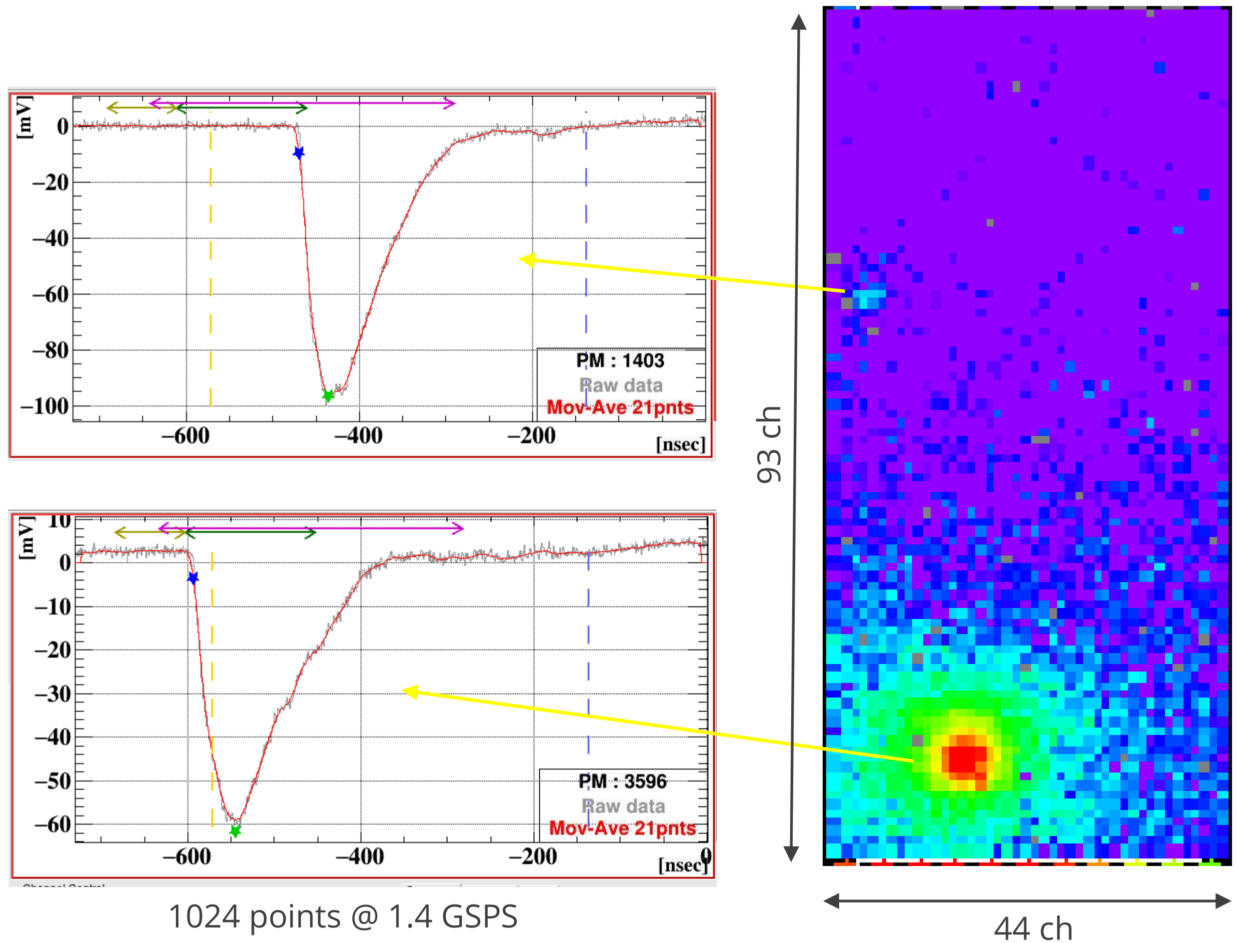


can be delayed scint. photon or afterpulse

Threefold pileup identification

1. Light distribution
2. Time distribution
3. Sum waveform



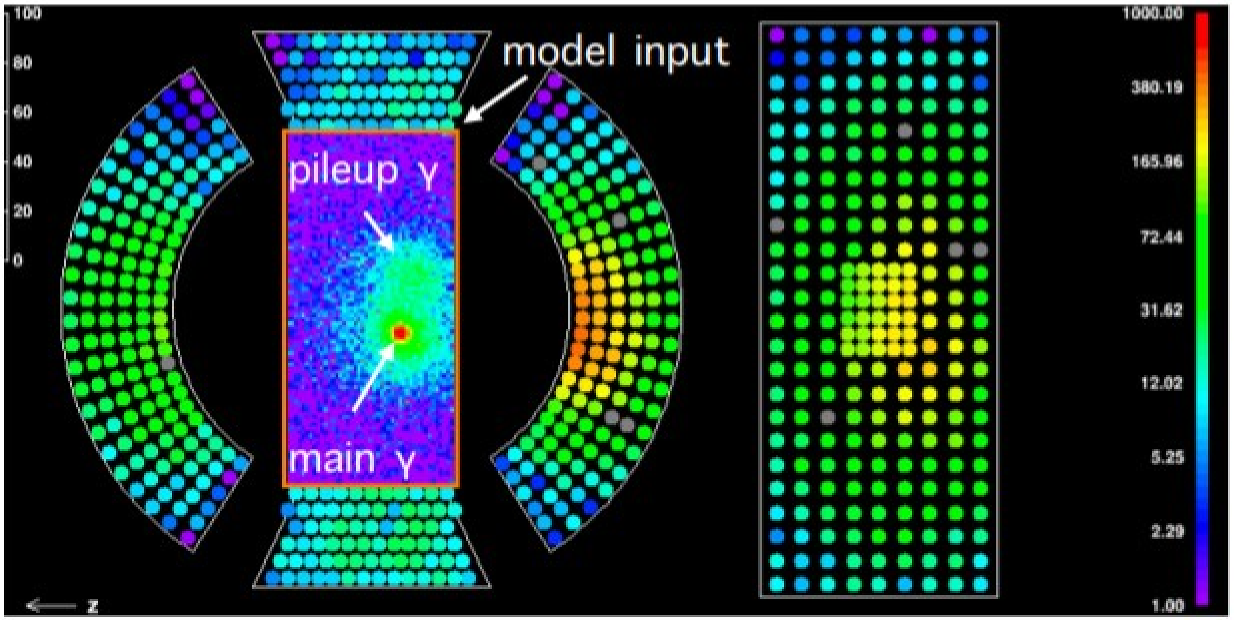


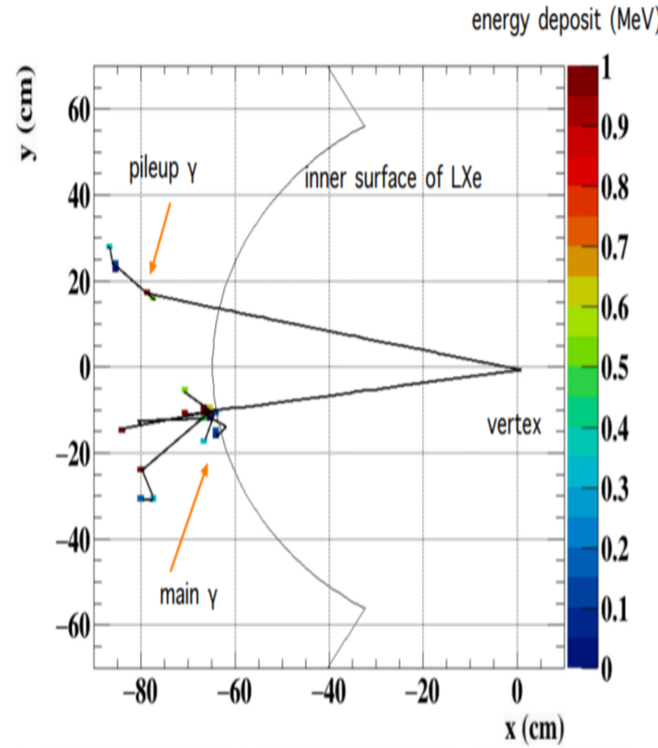
1024 points @ 1.4 GSPS

Limiting factors

1. Readout granularity (greatly improved in MEG II)
2. Dead channels
3. Electrical noise
4. Not only S/N but also absolute photon statistics
5. Waveform variation especially MPPC due to different afterpulse probability
6. Sensor time response (risetime and width of signal). MPPC has slower response than PMT.
7. Light propagation correction for timing
8. Non-uniformity, depth dependence
9. Isolated shower components

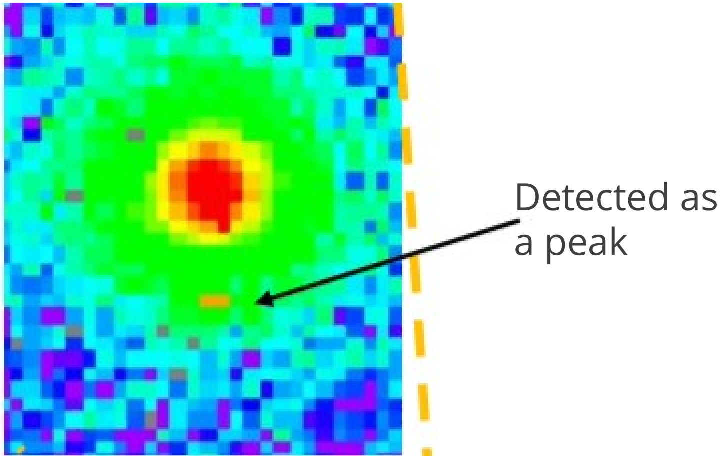
e.g. 1: deep pileup





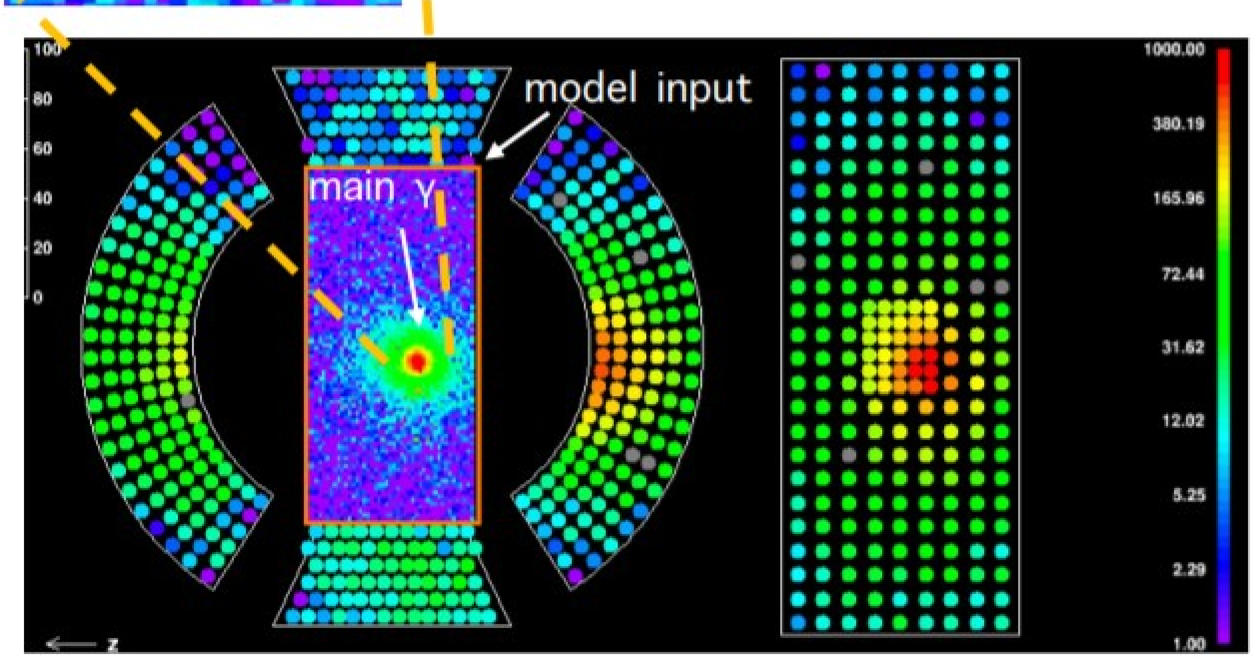
Peak search failed in detecting the pileup photon

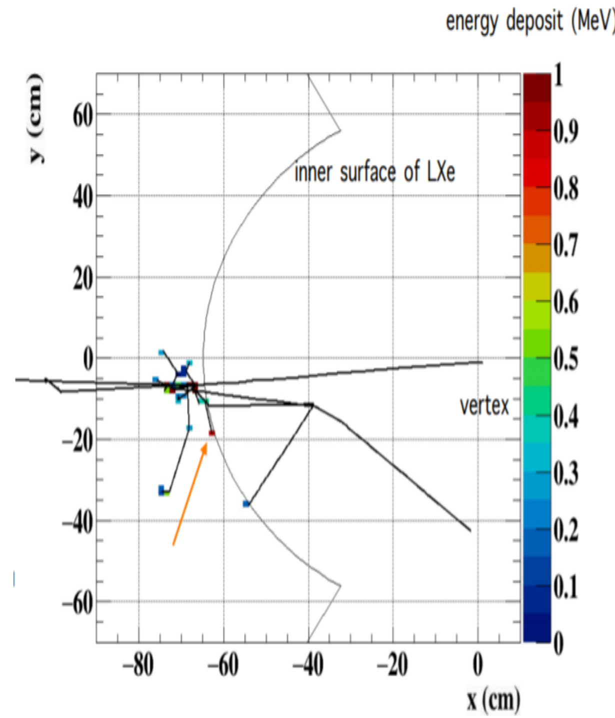
e.g. 2: fake peak



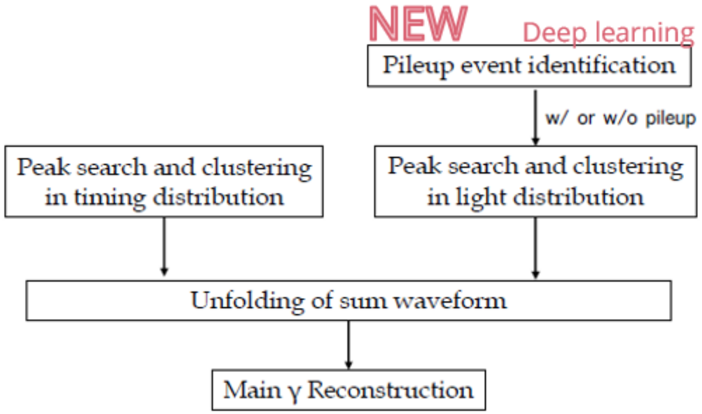
Peak search detects a fake photon

- Due to a peak from shower fluctuation



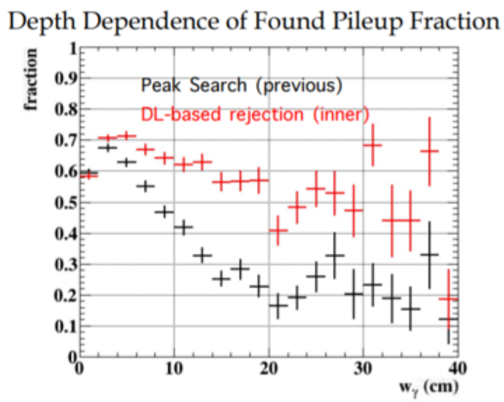


DL-based pileup ID on light distr.



Weak points of conventional peak search

1. Deep events that don't show a clear peak
2. Make a fake pileup from isolated energy deposit by shower fluctuation



DL model judges prob. of pileup event

- Based on 'EfficientNet'
- Implemented with Pytorch converted to ONNX
- Trained on Google Colab
- Input: 93×44 N_{pho} image
- Output: prob. to include pileup photons

So far, we haven't been able to use it (or any other DL models) for real data.

MC reproducibility

We lack a good reproducibility of LXe properties in our MC

Two major consequences

1. Doesn't reproduce response uniformity
2. Doesn't reproduce energy resolution

Point 1. comes from imperfect optical properties

- Such as reflectance on various materials, leading to errors in sensor calibration
- Even without perfect simulation, we can calibrate with data.
- So, we think this doesn't affect the performance, though better reproducibility make the life easier.

Point 2. we don't understand yet.

- Still remains in MEG II LXe detector
- We thought it may come from sensor instability, but it is now rejected
- Probably, comes from some LXe intrinsic properties, such as emission of infrared.
- Energy resolution is predominantly limited by this unknown factor

Don't rely on MC. Models trained and validated with MC don't work in reality.

Instead, take data (with prototype) and use them for training and validation.

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Charges in time slices

Peak search in light distribution is weak in detecting off-timing pileups

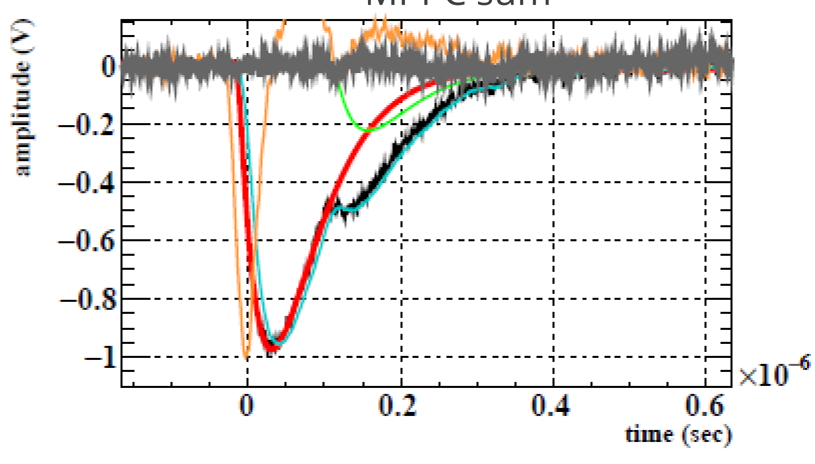
- Charge integration is done in on-timing window.
- Preceding pileup causes “negative” charges.

Possible improvement:

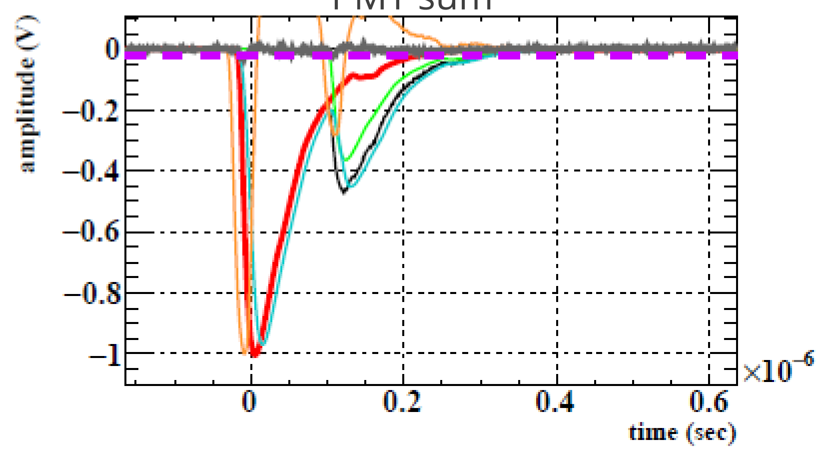
Making light distribution in different time slices.

Unfolding in sum waveform

If the pileup photon is temporally away (at least 5 ns in MEG, 30 ns in MEG II) from the main,
we can unfold them and measure the energy of the main.



(a)



(b)

- Sum waveforms are formed with all the calibrations taken into account
  → The integral directly gives the energy
- We don't discard such events

If close in time or coincident (such as AIF 2γ), discard.

Individual waveform?

Pileup identification/unfolding in each channel waveform is not effective due to p.e. statistics

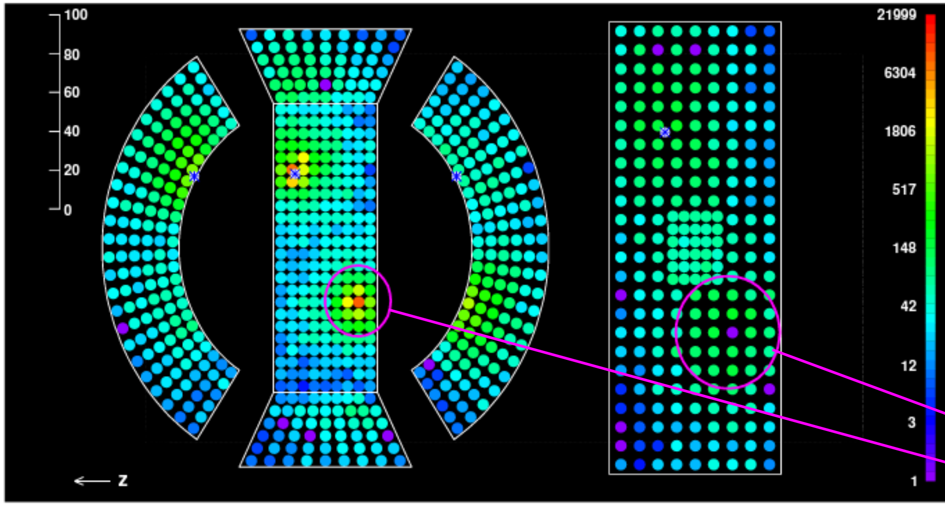
- Any attempts so far never succeeded. I don’t recommend for you to attempt it again.

Using total sum waveform is also not so much effective

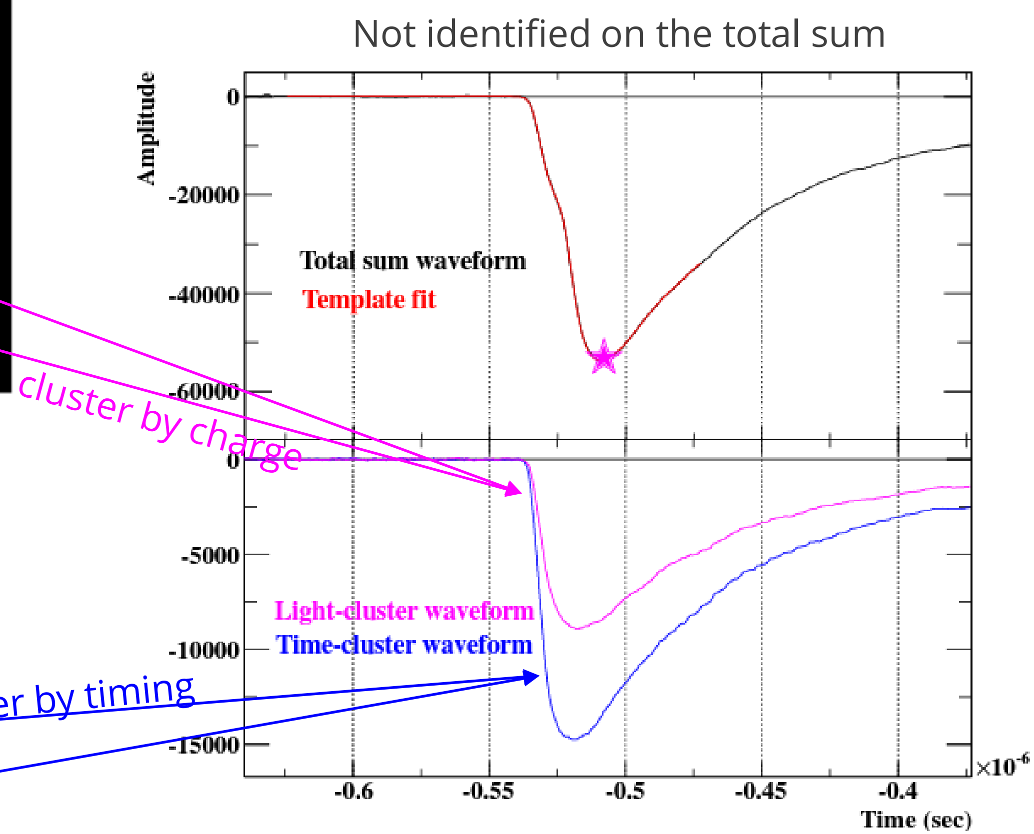
- Difficult to identify small pulses

Use sum waveforms in clusters or patch scan.

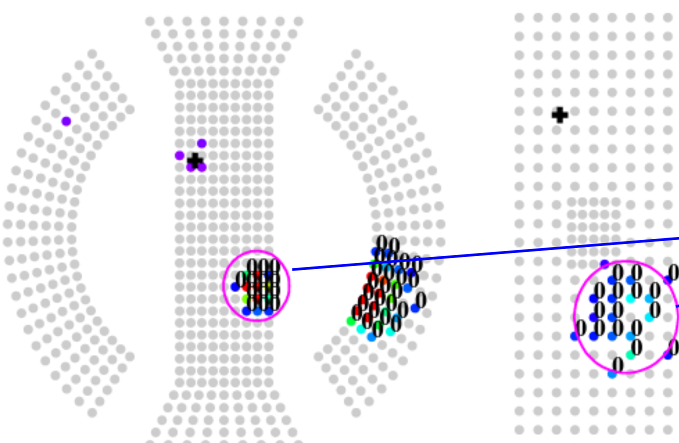
Unified approach



(a) Light distribution



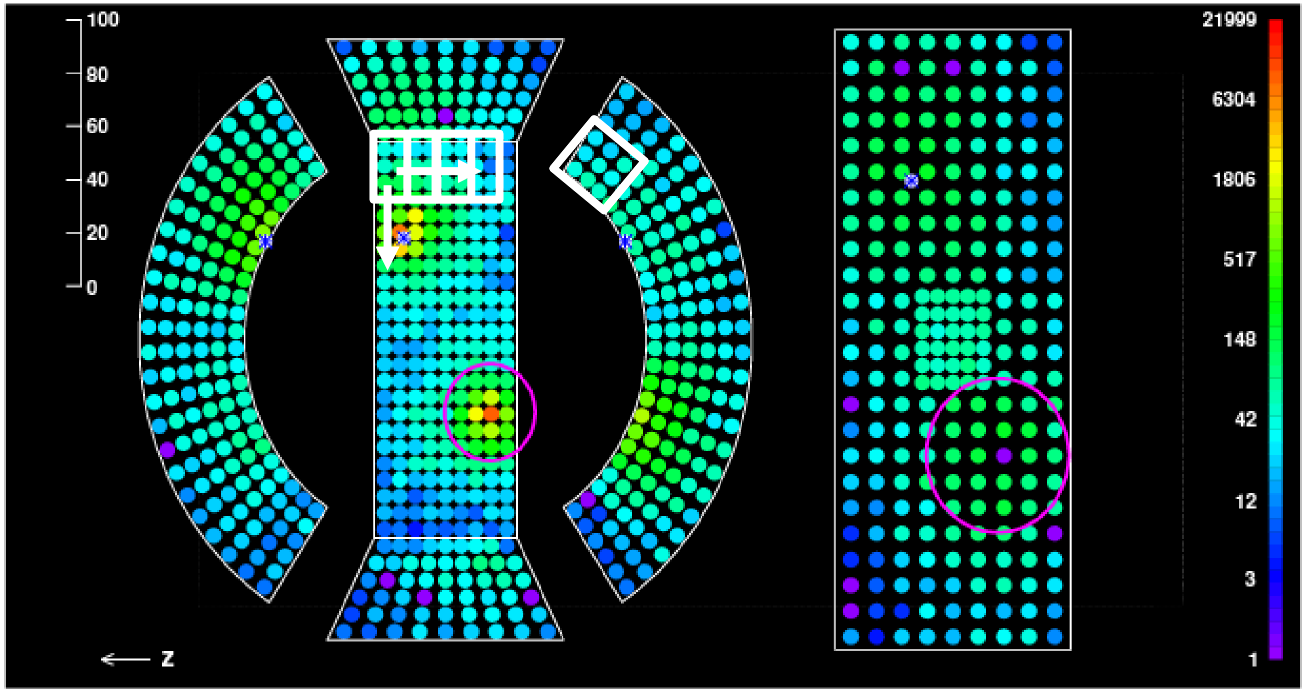
(c) Sum waveforms



(b) Distribution of large chi-square PMTs

These 2 clusters are recognized as the same, but different from the main
→ additional seed for the template fit.

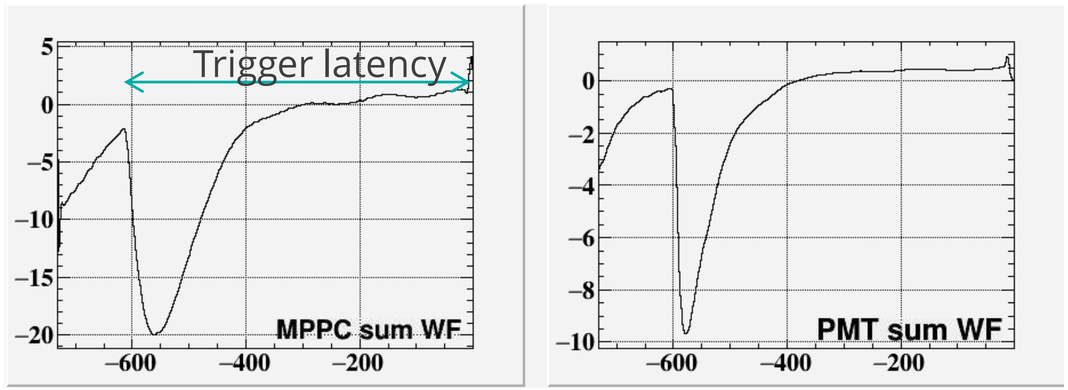
Patch scan?



Use of trigger FADC info

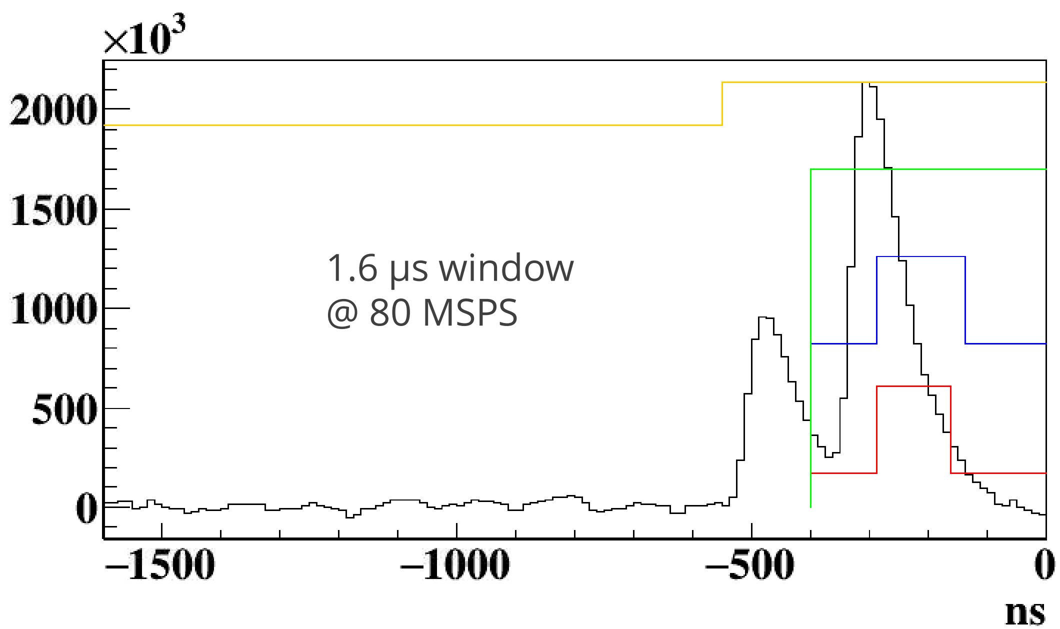
DRS time window is not wide enough to correctly unfold preceding pileup

- 730 ns window @ 1.4 GSPS,
- ~600 ns trigger latency



Trigger FADC has much wider window

- Can be used



How to evaluate inefficiency?

Difficult to evaluate the signal inefficiency due to the pileup analysis

1. Probability of having pileup in signal events and BG events are different due to triggering bias.
2. Difficult to completely simulate low-energy photon yield in MC
3. Fake probability is sensitive to threshold

In MEG II, we utilize the RDC detector

- RDC can identify RMD events, which is a single-photon process
- Check the fraction of discarded events in the RMD-identified sample → inclusive inefficiency

Conclusions

Pileup analysis is important in $\mu \rightarrow e\gamma$ search
Pileup is a source of high-energy BG,
Pileup analysis can cause inefficiency and low-energy tail.

We are still in developing stage for MEG II with real data.
Use and combine information as much as possible.
A few possible ways for improvement are discussed.
MC based ML study makes little sense.
Take data and use them.

There are many trade-off factors;
how to optimize parameters is also non-trivial task.